Magnetic Recording Configuration for Densities Beyond 1 Tb/in^2 and Data Rates Beyond 1 Gb/s

Kai-Zhong Gao and H. Neal Bertram, *Fellow, IEEE*

***Abstract*—A new magnetic recording system is evaluated that includes the single-pole head, a new medium design, and the soft underlayer of perpendicular recording. The proposed medium consists of perpendicular grains with anisotropy directions tilted optimally about 45° with respect to the perpendicular direction. Here, focus is on the tilt angle at 45° in the crosstrack direction, including a small but typical dispersion. The write pole consists of a tapered-neck single-pole head with a very small throat height that yields maximized write fields without increased edge track degradation. The advantages of tilted perpendicular recording are discussed using theoretical and numerical micromagnetic analyses. This design achieves a much higher signal-to-noise ratio (SNR) than conventional recording, because it is less sensitive to medium orientation distributions and, for the same thermal decay, can utilize media with much smaller grain sizes. The switching speed is much more rapid due to increased recording torque. Estimated recording limits for tilted perpendicular recording with a medium-jitter SNR of 17 dB are beyond densities of 1 Tb/in^2 and data rates of 1 Gb/s.**

***Index Terms*—Data rate, micromagnetic simulation, perpendicular recording, recording method, signal-to-noise ratio, thermal stability, tilted perpendicular recording, track edge effect, transition parameter.**

I. Introduction

MAGNETIC disk drives, for the last decade or more, have shown about a 100% growth rate. Current products are in the range of 20–40 Gb/in^2. Demonstrations of 60 Gb/in^2 and 100–130 Gb/in^2 have occurred for perpendicular and longitudinal recording, respectively [1]–[4]. It is generally thought that without medium distributions, at 20-dB medium signal-to-noise ratio (SNR) tolerance, longitudinal recording will face a limit of about 100 Gb/in^2 and perpendicular about 500 Gb/in^2 [5]. This argument is based on the thermal stability limit. In very high-density applications, the medium SNR varies, approximately, inversely as the cube of the in-plane grain diameter. Thus, growth in density has been accompanied by a decrease in grain diameter or volume. Decreasing grain volume leads to a reduction in thermal stability. Perpendicular recording alleviates this problem, because the perpendicular geometry favors a thicker medium. Thus, for a given thermal stability, perpendicular media can have a smaller in-plane grain diameter and, hence, higher SNR than longitudinal media.

Experimental measurements of perpendicular media have not immediately shown a distinct advantage [1]. Of course, material preparation is complicated. However, there are two fundamental issues: the maximum medium anisotropy limited by write-head saturation, and material property distributions that help explain these measured limitations [6]. In conventional perpendicular recording with well-oriented media, the coercivity (at short writing times) is slightly less than the grain anisotropy field. Utilizing the most advanced perpendicular head [6] for a typical geometry, the maximum field is about 0.73 B_s. Including an overwrite criterion, the maximum anisotropy field of the medium can be approximately 0.65 B_s. For example, for $B_s = 2.4$ T, $H_{k\max} \sim 15\,000$ Oe. Because of thermal effects, the maximum H_k limits the minimum grain diameter.

The problem of distributions has been examined by numerical micromagnetic simulations [7]–[9]. For perpendicular recording, even a small distribution in orientation (media are typically oriented within a cone angle of about 5°), as well as a small distribution in anisotropy magnitudes ($\sigma_{K_u}/\overline{K_u} \sim 0.1$[1]) significantly increases the recording transition parameter. This increase is reduced to some extent by a small amount of intergranular exchange [9]. The SNR varies strictly as the inverse of the square of the transition parameter times the crosstrack correlation width, e.g., [5]. Because the transition parameter depends on the distributions with a limiting minimum value related to the grain size, these effects further limit achievable densities of conventional perpendicular recording, to approximately 100–200 Gb/in^2.

One method to solve these problems is to redesign the record head so that the write field is somewhat angled with respect to the perpendicular direction [10]. This design permits a small increase (about 10%) in medium anisotropy field and, thereby, a slight decrease in grain diameter. This design also minimizes the effect of material distributions, reducing the transition parameter. The net effect is about a 2–3 dB improvement in SNR, bringing perpendicular performance closer to the idealized limit of [5]. The main problem with this design is that the fields exhibit an undershoot that extends significantly into the off-track region, which can cause multipass erasure. For this design, shielding is required in both the down and crosstrack directions. It has also been shown that a high linear density (1000 kfci) is achievable in conventional perpendicular recording using an inductive head [11]. There have been discussions of 1 Tb/in^2 recording, but the estimated SNR is limited to less than 10 dB [12]. However, none of the above approaches is able to significantly improve the current limits.

Here, we present a novel design that solves the current limitations of perpendicular recording, by a modification of the

Manuscript received April 30, 2002; revised July 15, 2002. This work was supported by Hitachi, Seagate Research, and an NSIC EHDR grant.

The authors are with the Center for Magnetic Recording Research, University of California at San Diego, La Jolla, CA 92093-0401 USA (e-mail: kgao@physics.ucsd.edu).

Digital Object Identifier 10.1109/TMAG.2002.804801

[1]Note that in this paper, the bar above a variable denotes the average value.

medium. We propose to use conventional recording transducers as currently proposed and to reorient the medium anisotropy axes to an angle optimally at about 45°. The anisotropy orientation can be either in the downtrack or the crosstrack direction or even randomly in a plane at a fixed angle with respect to the perpendicular direction. However, here we consider only the case of the anisotropy angle tilted in the crosstrack direction. This design has many benefits. First, the effects of orientation distributions are virtually eliminated, substantially more than the design of [10]. Second, a medium with a significantly larger anisotropy field, approximately $H_k \sim 1.2B_s \sim 28\ 000$ Oe, can be utilized. Third, a much higher data rate can be achieved, because the reversal time of this new configuration is so efficient with regard to reversal torque: the reversal times for both writing and overwrite are independent of the medium properties and depend solely on the field rise time. Fourth, multipass edge track erasure is reduced due to increased grain energy barriers. Using an analysis similar to [5], the estimated density limit of this tilted perpendicular recording is about 1.3 Tb/in^2 with a medium-jitter SNR of 17 dB [isolated peak pulse to high-density root-mean-square (rms) transition noise], at an operating temperature of 360 K, and a data rate limit above 1.5 Gb/s. (Here, we assume the medium has a very small medium grain size distribution with $\sigma_A/\bar{A} = 0.3$, a very small anisotropy orientation distribution typically within a 5° cone angle and a very small H_k magnitude $\sigma_{H_k}/\bar{H}_k = 0.05$ distribution).

The possibility of tilted media in perpendicular recording has been mentioned previously [13]. Tilted longitudinal recording has been developed in metal evaporated (ME) tape recording [14], [15]. Utilizing an inductive head with tilted medium, the SNR of the tape recording system is improved [15]. Recently, tilted longitudinal recording has also been proposed for disk recording [16]. Both experiment and simulation show a possible extension of current longitudinal recording [16], [17].

In this paper, both tilted perpendicular and conventional perpendicular recording are investigated using both analytic and numerical micromagnetic simulations. The specific evaluation for 200 Gb/in^2 is given to show how this new design facilitates recording at this density. The tilted perpendicular recording scheme is described in Section II, including tilted perpendicular medium parameters with H_k (both orientation and magnitude) distributions. The thermal stability limit and the minimum medium grain size are derived in Section III. In Section IV, numerical simulations of the recording transition parameter are shown. These results are discussed based on the William Comstock model. Track edge effects are discussed in Section V. Medium switching speed and the data rate limit are presented in Section VI. In Section VII, a simple estimate of SNR in both tilted and conventional perpendicular recording is obtained and comparison plots of SNR versus density are shown. A brief discussion of the effects of intergranular exchange, alternative media, and large distributions on the recording limits is given in Section VIII.

II. Tilted Perpendicular Recording Scheme/Material Parameters

A. Tilted Perpendicular Recording and Model Geometry

In Fig. 1, the new magnetic recording configuration is illustrated. The medium anisotropy easy axis is tilted in a fixed direction, which, for the analysis here, is angled at about 45° in the crosstrack direction. Note that for the study here, the media grains are still oriented in the perpendicular direction; only the anisotropy easy axes are tilted. As shown in [18], the recording head is a previously described tapered-neck structure. Parameters corresponding to 200 Gb/in^2 [5] are illustrated in Fig. 1(a) and (b). The tapered-neck pole with a very small throat height is shown in Fig. 1(a) (downtrack view). The write pole track width and the pole thickness are 120 and 300 nm, respectively. The write pole throat height is 60 nm [18]. The soft underlayer (SUL) thickness is chosen to be 300 nm with permeability $\mu = 400$ and $M_s^{\rm SUL} = M_s^{\rm tip} = 1900$ emu/cc ($B_s = 4\pi M_s \approx 2.4$ T). For 200 Gb/in^2 optimum design, the flying height is 10 nm, the medium thickness is 20 nm, and the growth layer between the medium and the SUL is 5 nm.

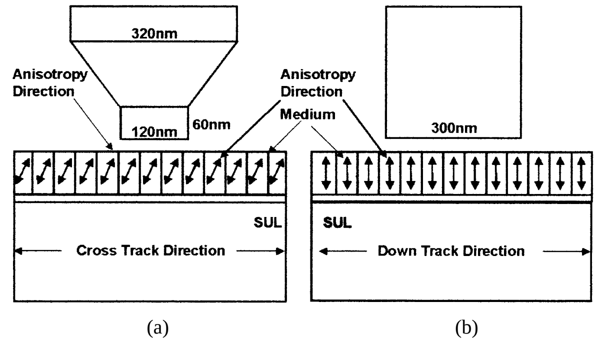


Fig. 1. Typical geometry of tilted perpendicular recording at 200 Gb/in^2. In this example, the medium anisotropy directions, not the medium grains, are tilted in the crosstrack direction. (a) Downtrack view. (b) Crosstrack view. Note for clarity, the grain diameter is not to scale.

In our three-dimensional (3-D) simulation, the write pole and the SUL are discretized into 20-nm^3 uniformly magnetized cubic cells. In the medium, the intrinsic cell size is 2 nm × 2 nm times the medium thickness. A grain size distribution is included by grouping these cell units into single-domain grains utilizing a modified Voronoi distribution [19], [20]. During the simulation cycles, computation time is saved by using a two-dimensional fast Fourier transform (2-D FFT) for the magnetostatic fields in the film plane direction. In addition, when the fields due to the medium in the pole tip and the SUL are computed, the medium magnetization is averaged over cubes with side length equal to the medium thickness. H_k orientation (typically within a 5° cone angle) and magnitude distributions (typically $\sigma_{K_u}/\overline{K_u} \le 0.1$) are applied to each medium grain. A fixed small anisotropy of about 20 Oe in the crosstrack direction is applied to the pole tip and the SUL. The simulations solve coupled Landau–Lifshitz equations simultaneously at each cell to model the magnetization reversal and to obtain the equilibrium state [21]

$$\frac{d\vec{M}}{dt} = -\gamma(\vec{M} \times \vec{H}) - \frac{\alpha\gamma}{M_s}(\vec{M} \times (\vec{M} \times \vec{H}))$$
$$\vec{H}_{\rm eff} = -\frac{\partial E}{\partial \vec{M}}. \qquad (1)$$

In (1), E is the energy density comprising the applied field, the anisotropy field, the exchange, and magnetostatic interactions.

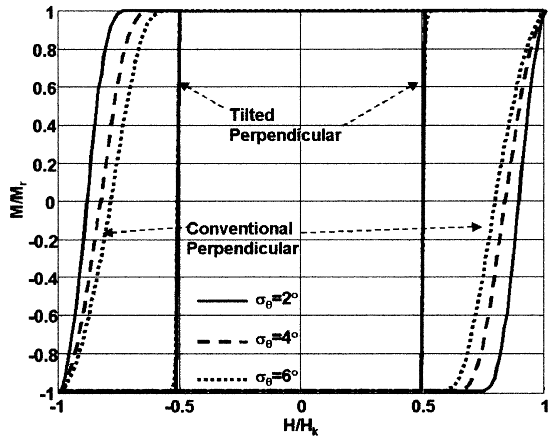


Fig. 2. Intrinsic (de-sheared) remanent M–H loop for both tilted and conventional perpendicular media with only an orientation distribution.

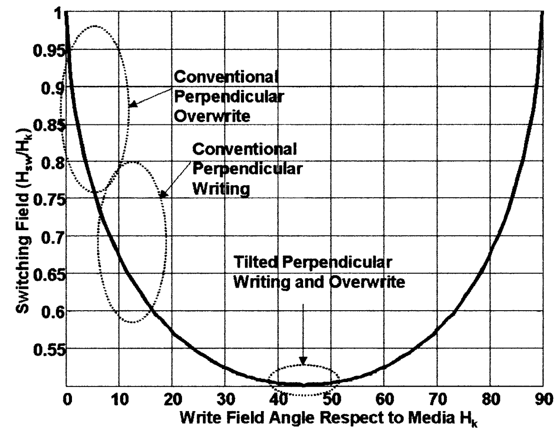


Fig. 3. Medium switching field and overwrite field in both tilted and conventional perpendicular recording media.

B. Distribution Sensitivity

Fig. 2 shows the intrinsic (de-sheared) remanent M–H loop calculated without interactions using only the orientation distribution for both tilted and conventional perpendicular media. We assume that the medium anisotropy easy axes have a typical normal distribution with $\sigma_\theta = 2^\circ, 4^\circ$, and 6° respectively. For tilted media, these distributions are with respect to a mean orientation of 45° from the perpendicular direction. As shown in Fig. 2, in tilted perpendicular media, the remanent coercivity is $H_c \approx 0.51\bar{H}_k$ and virtually no effect of orientation distribution is seen $(S^* \sim 1)$. For conventional perpendicular media, the coercivity is much higher, $H_c \approx 0.8\bar{H}_k$, depending on the orientation distribution. The loop squareness (S^*), which strongly effects the transition parameter, decreases with increasing orientation distribution ($S^* = 0.91, 0.87, 0.84$ for $\sigma_\theta = 2^\circ, 4^\circ, 6^\circ$, respectively). S^* is further decreased for both media when a distribution of anisotropy magnitudes is included.

These results can be explained using the Stoner–Wohlfarth switching field for a single uniformly magnetized grain [22]

$$h_{\rm sw}(\theta) = \frac{1}{(\cos^{2/3}(\theta) + \sin^{2/3}(\theta))^{3/2}} \qquad (2)$$

where $h_{\rm sw} = H_{\rm sw}/\bar{H}_k$, and θ is the angle between the applied field and the grain anisotropy direction. Fig. 3 shows the single-particle switching field $(H_{\rm sw})$ versus external field angle (with respect to the medium anisotropy easy axis). For a small field angle, the medium switching field decreases significantly with increasing field angle. In conventional perpendicular recording, both the writing field at the transition center and the overwrite field in the gap have a small angle with respect to the medium anisotropy easy axis (typically about 5° for overwrite and 12° for writing). In conventional perpendicular recording, these small angles coupled with the medium anisotropy orientation distribution causes a large switching field distribution (solid curves inside the dotted bubbles in Fig. 3), a decreasing medium coercivity (Figs. 2 and 3), and a decreasing loop squareness (Fig. 2).

In our tilted perpendicular recording system, the write field and overwrite field from the single-pole head are (almost) in the perpendicular direction. Both the writing and overwrite field are about 45° with respect to the medium anisotropy direction. As shown in Fig. 3, the medium switching field for tilted perpendicular recording is insensitive to a small angle variation due to either the external field or medium anisotropy distributions. As a result, the medium loop squareness $(S^* \sim 1)$ hardly changes with increasing H_k orientation distribution.

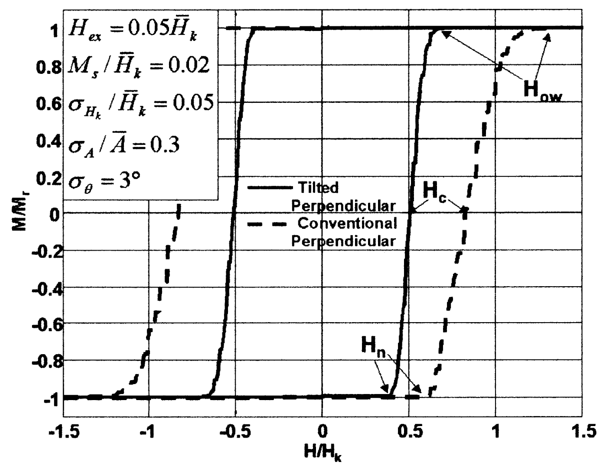


Fig. 4. Micromagnetic simulation results of the remanent M–H loop for both tilted and conventional perpendicular media.

The micromagnetic simulation results of the M–H loops for both tilted and conventional perpendicular medium are shown in Fig. 4. In our simulation, the scaled medium magnetization is $M_s/\bar{H}_k = 0.02$, and the scaled exchange is $h_{\rm ex} = H_{\rm ex}/\bar{H}_k = 0.05$. A 3° normal anisotropy orientation distribution and a log normal anisotropy magnitude distribution with $\sigma_{H_k}/\bar{H}_k = 0.05$ are utilized (a variance of 3° in a normal distribution corresponds to a 5° in a uniform distribution). The results show: 1) the tilted perpendicular medium coercivity is $H_c \approx 0.5\bar{H}_k$ versus $H_c \approx 0.8\bar{H}_k$ in conventional perpendicular media; 2) the overwrite (closure) field in tilted perpendicular media is $H_{\rm ow} = 0.67\bar{H}_k$ versus $H_{\rm ow} = 1.25\bar{H}_k$ in conventional perpendicular media; and 3) the medium nucleation field in a tilted perpendicular medium is $H_n \approx 0.4\bar{H}_k$ versus $H_n \approx 0.6\bar{H}_k$ in a conventional perpendicular medium. As we discuss later, these differences have a significant effect on ultrahigh-density recording.

TABLE I
MAXIMUM ANISOTROPY ESTIMATES FOR BOTH TILTED AND CONVENTIONAL PERPENDICULAR RECORDING MEDIA

	TP	CP
$\bar{H}_k(Oe)$	$28,000$	$15,000$
$M_s(emu/cc)$	560	300

C. Maximum Anisotropy Field

Here, we estimate the maximum anisotropy field in a simplified manner. As shown in Fig. 3, for a medium grain oriented near 45°, the coercivity H_c is approximately

$$H_c \approx 0.51\bar{H}_k. \quad (3)$$

To completely saturate the medium, the required field is

$$H_{\mathrm{ow}} \approx 0.51\bar{H}_k + 4\pi M_s/\sqrt{2} \quad (4)$$

where the latter term is the demagnetizing field reduced by the cosine of the tilt angle (approximately 45°). Although the magnetostatic field is, except for extremely hard pole tip saturation, less than this value due to the presence of the highly permeable SUL [5], we use the single keeper result here. The tapered single-pole head design gives a maximum write field of approximately $0.80B_s$ in the medium without decreasing the field gradient in the crosstrack direction [23]. For a material with $B_s = 2.4$ T, the maximum write field is approximately 1.9 T.

As shown in Table I, the maximum anisotropy field for tilted perpendicular recording is about 28 kOe. Utilizing a criterion of $H_{\mathrm{ow}} \approx H_c + 4\pi M_s \approx 0.9\bar{H}_k + 4\pi M_s$ for conventional perpendicular yields a maximum anisotropy field of approximately $\bar{H}_k \approx 15$ kOe. As shown in Fig. 4, this estimate is consistent with the numerical simulation results.

III. MINIMUM GRAIN DIAMETER AND THERMAL STABILITY

A simple estimate of thermal stability in perpendicular media can be made utilizing [24]

$$M(t) = M_r e^{-t_{\max} f_0 e^{-E_b/kT}} \quad (5)$$

where the probability of grain reversal back into the original equilibrium is neglected. In (5), E_b is the reversal energy barrier, $t_{\max}$ is the maximum elapsed time (here, $t_{\max} = 10$ years), $k_B = 1.38 \times 10^{-16}$ ergs/K is the Boltzmann constant, and T is the temperature in degrees kelvin. As discussed in [25], the thermal attempt frequency f_0 is given approximately by

$$f_0 \sim 2\alpha\gamma H_k \sqrt{\frac{4K_uV}{\pi k_B T}}\,(1 - h_{\mathrm{demag}}/h_{\mathrm{sw}}(\theta))^2 \frac{1}{h_{\mathrm{sw}}(\theta)^3} \quad (6)$$

where α is the relaxation parameter with a typical value of 0.01, K_u is the anisotropy constant of the media, and $\gamma = 1.76 \times 10^7$ (Oe)$^{-1}$ is the gyromagnetic ratio. Here, to estimate f_0, in (6), a typical value of $K_uV/k_BT \sim 90$ is utilized. Note that in the following analysis, (6) is utilized; f_0 is typically about 10^{11}, which is much larger than the commonly used estimate of 10^9.

Assuming a sufficiently large energy barrier so that the magnetization has decreased by half after ten years, then

$$E_b/k_BT = \ln(t_{\max} f_0/\ln 2). \quad (7)$$

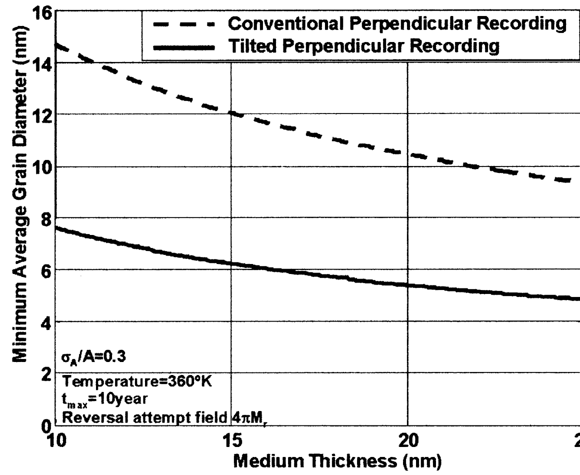


Fig. 5. Minimum average grain diameter versus medium thickness for tilted and conventional perpendicular recording. At $T = 360°$ K, $t_{\max} = 10$ years.

The energy barrier in tilted perpendicular media is

$$\begin{aligned} E_b &= K_uV(1 - h_{\mathrm{demag}}/h_{\mathrm{sw}}(\theta))^{3/2} \\ &= \frac{H_kM_s}{2}D^2t(1 - 4\sqrt{2}\pi M_s/H_k)^{3/2} \end{aligned} \quad (8)$$

where $V \sim D^2t$, and t and D are the medium thickness and grain diameter, respectively. A worst case situation (neglecting exchange) is considered far from the transition center where h_{demag} is maximum. Inclusion of a grain size distribution simply causes V to be replaced by the distribution rms value $(\overline{V^2})^{1/2}$ [26]. Thus, using (6) and (8), the minimum in-plane rms grain diameter for tilted perpendicular media is

$$D_{\mathrm{rms}}^{\mathrm{TP}} = \sqrt{\frac{2k_BT\ln(t_{\max}f_0/\ln 2)/H_kM_st}{(1 - 4\sqrt{2}\pi M_s/H_k)^{3/2}}}. \quad (9)$$

In conventional perpendicular media

$$\begin{aligned} E_b &= K_uV(1 - h_{\mathrm{demag}}/h_{\mathrm{sw}}(\theta))^2 \\ &= \frac{H_kM_s}{2}D^2t(1 - 4\pi M_s/H_c)^2 \end{aligned} \quad (10)$$

and the minimum in-plane rms diameter is

$$D_{\mathrm{rms}}^{\mathrm{CP}} = \frac{\sqrt{2k_BT\ln(t_{\max}f_0/\ln 2)/H_kM_st}}{(1 - 4\pi M_s/H_c)}. \quad (11)$$

Fig. 5 shows the average medium grain diameter versus medium thickness in both tilted and conventional perpendicular recording due to the above thermal stability constraints. Both media are assumed to have a grain size distribution of $\sigma_V/\bar{V} = \sigma_A/\bar{A} \sim 0.3$ (a fixed grain height equal to the medium thickness is assumed). $\bar{D}$ can be obtained from (9) and (11) ($\bar{D} = D_{\mathrm{rms}}\exp(-\beta^2/8)$, where $\beta = \sqrt{2\ln(1 + \sigma_V^2/\bar{V}^2)}$ for a log normal distribution). The results utilize $T = 360$ K, $t_{\max} = 10$ years, and $K_u\bar{V}/k_BT \gtrsim 90$. Fig. 5 shows that for the same recording medium thickness, the average grain diameter in tilted perpendicular media is about half that of conventional perpendicular media. For a medium thickness of 15 nm, the average grain diameter for tilted perpendicular

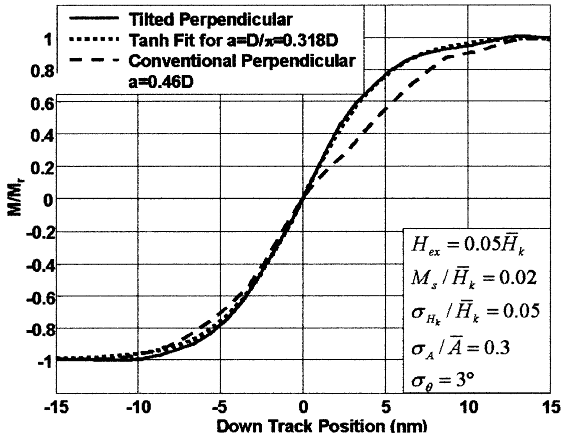


Fig. 6. Typical transition parameter for both tilted and conventional perpendicular recording.

media is about 6.2 nm compared to 12 nm for conventional perpendicular media. In this estimate, a temperature decrease of $H_k = 0.08\%$ per degree kelvin is included [27], [28]. Note that utilizing the results in Section II-A and (9) and (11), we have $K_u\bar{V}/k_BT \gtrsim 90$ for both tilted and conventional perpendicular media.

IV. Transition Parameter

In this section, the results of micromagnetic simulation for the transition parameter in both tilted and conventional perpendicular recording media are presented. These results are discussed in terms of a simple analysis based on the Williams–Comstock formulation [29].

A. Micromagnetic Simulation

Fig. 6 shows micromagnetic simulation results of recorded transitions for both tilted and conventional perpendicular media. In the simulation, ten transitions were written and single average magnetization patterns are shown for each. This simulation is two-dimensional with a uniform write field across the track width. The specific form of the write field comes from the center track field of the tapered single-pole head [18]. For both tilted and conventional perpendicular media, the simulations assume $M_s/\bar{H}_k = 0.02, H_{\rm ex} = 0.05\bar{H}_k$, and medium distributions of anisotropy field angle $\sigma_\theta = 3°$, anisotropy magnitude $\sigma_{H_k}/\bar{H}_k = 0.05$, and grain size volume $\sigma_V/\bar{V} = 0.3$. The average grain diameter from (9) and (11) is chosen to be $\bar{D} \approx 10$ nm. The transitional shape for conventional perpendicular media is asymmetric due to the head field spatially asymmetry and the importance of material distributions in this case. Therefore, we estimate the transition parameter by averaging fits to both sides of the transition. The simulation results show that the transition parameter in tilted perpendicular medium is 3.2 nm $(\sim D/\pi)$, close to the theoretical limit. The transition parameter for conventional perpendicular recording is estimated from Fig. 6 to be about 4.5 nm. From Fig. 5, the thermal limits give a minimum grain size for conventional perpendicular medium twice that of tilted perpendicular media. Thus, the ratio of transition parameters is approximately 2.8 (2×4.6 nm / 3.2 nm). As will be discussed in Section VII, this effect yields a major improvement in SNR for tilted perpendicular media.

B. Discussion Utilizing the Williams–Comstock Model

A simple form for the transition parameter is given by Williams–Comstock formula [29]

$$\frac{dM}{dx} = \frac{dM}{dH}\left(\frac{dH_{\rm head}}{dx} - \left|\frac{dH_{\rm demag}}{dx}\right|\right) \tag{12}$$

where

$$\frac{dM}{dH} = \frac{1}{(1-S^*)}\left(\frac{M_r}{H_c}\right). \tag{13}$$

For this discussion, all fields and field gradients are evaluated at the transition center corresponding a maximum field gradient. Independent of the specific transition shape, the magnetization gradient is given by $dM/dx = 2/\pi a$, where a is the transition parameter [30]. Note that the Williams–Comstock analysis does not explicitly include the effects of finite grain diameter and intergranular exchange.

First, we discuss the effect of the M–H loop shape (13). As can be seen in Fig. 2, in conventional perpendicular recording, including orientation distribution, for $\sigma_\theta = 4°, S^* \approx 0.87$.[2] Utilizing a small exchange and an alternative write head design [10], S^* can increase to approximately 0.95. In tilted perpendicular recording, as shown in Fig. 2, S^* is very close to 1 (approximately 0.99). Thus, we have $dM/dH_{\rm tilted} \gg dM/dH_{\rm perp.}$, which leads to a smaller transition parameter for tilted perpendicular media. Note that $M_r/H_c \approx 0.7M_s/0.5\bar{H}_k \approx 0.028$ in 45° tilted perpendicular media, and $M_r/H_c \approx M_s/0.8\bar{H}_k \approx 0.025$ in conventional perpendicular media. However, this comparison overestimates the effect of the loop shape, because the large S^* for tilted perpendicular media makes the transition parameter limited by the grain size.

In tilted perpendicular media, the magnetostatic field gradient magnitude $[dH_{\rm demag}/dx]$ is reduced compared to conventional perpendicular media, which also yields a smaller relative transition parameter. In conventional perpendicular recording, $[dH_{\rm demag}/dx] \propto M_s$, while in tilted perpendicular recording, $[dH_{\rm demag}/dx] \propto M_s\cos(\theta) \sim M_s/\sqrt{2}$. Because the magnetostatic field gradient varies approximately inversely with the transition parameter [30], the decreased magnetostatic field gradient in tilted perpendicular recording acts to decrease the transition parameter. Numerical micromagnetic simulations confirm the results of the qualitative predictions in this section.

C. Effect of Spatially Varying Field Angle

The Williams–Comstock model [29] can be utilized for media with a fixed coercivity. However, as shown before [18], in perpendicular recording, the write field angle from a single-pole head increases with distance from the trailing (leading) edge. From Fig. 3, the field angle change in perpendicular recording causes a spatially varying change in medium coercivity. This

[2]The S^* in this section refers to the medium intrinsic loop squareness. Here, the anisotropy magnitude (H_k) distribution is not included.

effect maybe included in the Williams–Comstock criterion by approximately subtracting the spatial variation of the coercivity

$$\frac{dM}{dx} \approx \frac{dM}{dH}\left(\frac{dH_{\text{head}}}{dx} - \left|\frac{dH_{\text{demag}}}{dx}\right| - \frac{dH_c}{dx}\right). \tag{14}$$

In conventional perpendicular recording, as shown in Fig. 3, as the small write field angle increases, the medium coercivity decreases significantly. Close to the transition center, dH_c/dx and dH_{head}/dx are in the same direction: the net effect gives a decrease of the effective write field gradient as compared to (12). Thus, this effect for conventional perpendicular recording tends to increase the transition parameter. In tilted perpendicular recording, the write field angle with respect to the perpendicular direction increases with distance away from the trailing (leading) edge: the medium coercivity increases with decreasing write field (increasing field angle); dH_c/dx and dH_{head}/dx are in the opposite direction. Therefore, for tilted perpendicular recording, the effective write field gradient increases as compared to (12) and tends to decrease the transition parameter.

V. Track Edge Effect

In the presence of a reverse field at a fixed angle with respect to the perpendicular direction, the energy of a single grain from the Stoner–Wohlfarth model is approximately [31], [32]

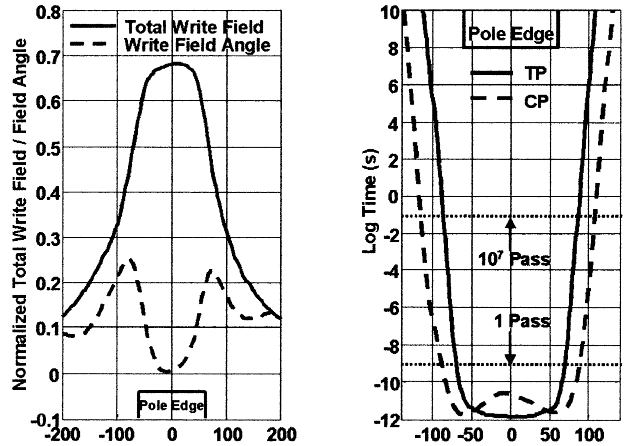
$$E_b = K_u V(1 - h_r/h_{\text{sw}}(\theta))^{3/2} \tag{15}$$

where h_r is the normalized reverse field, scaled to $H_k(h_r = H_r/H_k)$. θ is the write field angle respect to the anisotropy direction of the medium. The switching field versus write field angle is given by (2) [22].

Fig. 7(a) shows the total write field and field angle under the tapered write pole in the crosstrack direction. For a write track pole width of 120 nm, the results show that close to the write pole edge, initially, the write field angle with respect to the perpendicular direction increases (from zero) with off-track position (from 0 to ± 80 nm). Beyond ± 80 nm, the field angle decreases with distance away from the write pole. Therefore, in conventional perpendicular recording, to a distance of about 30% of the write pole width, the coercivity and thus the energy barrier is decreased. In tilted perpendicular recording, the increased field angle reduces the relative angle between the field and the medium grains orientation (around 45°). Thus, the energy barrier increases with off-track position.

Fig. 7(b) plots the medium reversal time versus crosstrack direction for both tilted and conventional perpendicular medium due to the external field from Fig. 7(a). Both curves are obtained utilizing (5) and (6). For a thermal reversal criterion, here we assume a 1-dB decay in ten years. For typical perpendicular recording, the write pole downtrack thickness is about 2–300 nm ($PT = 2$–300 nm) with disk velocity typically about $v = 20$–30 m/s. In this case, 10 million passes correspond to $t = 10^7 \times PT/v = 10^{-1}$ s. For one pass, we consider only dynamic reversal $H = H_c$ for both cases.

The results in Fig. 7(b) show that there are two significant differences between tilted and conventional perpendicular recording: First, as shown in Fig. 7(b), in the dynamic region (neglecting thermal effects), the write width in tilted



(a) (b)

Fig. 7. (a) Total write field and field angle from tapered single-pole head. (b) Medium reversal time versus crosstrack position for both tilted perpendicular (TP) and conventional perpendicular (CP) recording.

perpendicular recording is only about 10% larger than the write pole width (one pass position of the dotted curve). On the other hand, in conventional perpendicular recording, the actual write width is about 40% larger than the write pole width. This means that utilizing the same write pole geometry, tilted perpendicular recording can achieve higher track density as compared to conventional perpendicular recording. Or, for the same recording density, a larger write pole width can be utilized in tilted perpendicular recording as compared to conventional perpendicular recording, which also increases the total achievable write field.

Second, the write field in the crosstrack direction may cause erasure of neighboring tracks. In Fig. 7(b), the 10 million passes position shows the total write width (write track width plus erasure band) in both tilted and conventional perpendicular recording. For a write pole width of 120 nm, the total write width is about 165 nm in tilted perpendicular recording, while for conventional perpendicular recording, the total write width is about 240 nm. Therefore, for a 120-nm write pole, the recording track width for tilted perpendicular recording is 142 nm versus 180 nm in conventional perpendicular recording. Note that for a real recording system, two neighboring tracks share the erase (guard) band.

This effect allows for a higher track pitch density for tilted perpendicular recording as compared to conventional perpendicular recording. A simple way to estimate this effect is, for a fixed system with a given SNR, the areal density for conventional perpendicular recording should be reduced by 20% (180 nm/142 nm).

VI. Dynamics

Fig. 8 shows medium switching time versus damping constant for both tilted and conventional perpendicular recording using numerical simulation. For this study, the recording field is assumed to be uniform over the medium in the perpendicular direction with a time variation $H(t) = H_0(1 - 2e^{-t/\tau})$, where $\tau = 0.05$ ns. The field magnitude is $H_0 = 1.2\bar{H}_k$ for conventional perpendicular recording. For tilted perpendic-

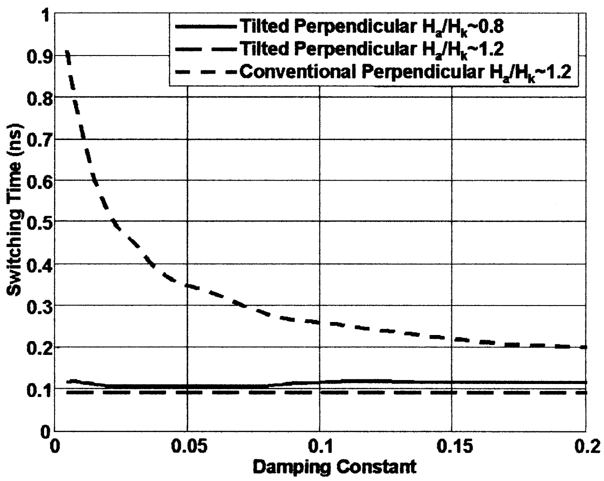


Fig. 8. Tilted and conventional perpendicular medium switching time versus damping constant.

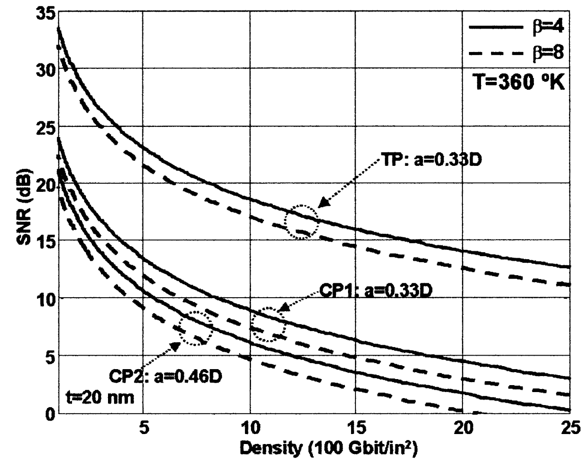


Fig. 9. SNR for tilted perpendicular (TP), case 1 (CP1), and case 2 (CP2) of conventional perpendicular recording at $T = 360$ K, $M_s/H_k = 0.02$. β is the bit-aspect ratio.

ular recording, we show two cases: $H_0 = 1.2\bar{H}_k$, and $0.8\bar{H}_k$. (Note: for same write field $0.8\bar{H}_k$ versus $1.2\bar{H}_k$ correspond to a 50% gain in $\bar{H}_k$). The simulation parameters are grain size distribution $\sigma_A/\bar{A} \sim 0.38$ and anisotropy magnitude distribution $\sigma_{H_k}/\bar{H}_k \sim 0.05$. The medium magnetization is $M_s = 0.025\bar{H}_k$. The irreversible switching speed is defined in [33] and [34], with switching time beginning when the reversal field is equal to the medium coercivity. Final switching is defined when 50% of the medium grains have switched.

The results show that tilted perpendicular medium switching is much faster than for conventional perpendicular media. The reason is that the head field has a much larger angle in tilted perpendicular recording. Therefore, a much larger torque is applied to the medium at the beginning of the reversal. In conventional perpendicular media, the switching time decreases with increasing damping constant in contrast to tilted perpendicular media where the switching time is almost independent of damping constant. From the discussion in [34] and [35], in tilted perpendicular recording, the switching speed is similar to that of longitudinal recording. Note that the switching speed for conventional perpendicular media may be faster than the estimate of Fig. 8 due to recent theories about nonlinear damping [36].

VII. SNR Estimate

To estimate the SNR, we assume both tilted and conventional perpendicular media will be characterized by the dominant transition noise. Following [5], we use the definition of a maximum signal (square) of an isolated transition divided by the rms transition noise in square wave recording at bit separation B. A good approximation for this SNR is [37]

$$\mathrm{SNR} = \frac{0.324 T_{50} B W_r}{a^2 s_c} \tag{16}$$

where T_{50} is the pulsewidth without differentiation. B is the transition spacing, W_r is the read track width, a is the transition parameter, and s_c is the crosstrack correlation width. Because the pulse is not changed for tilted perpendicular recording angled in the crosstrack direction, (16) can be immediately applied. Here, we assume $\mathrm{PW}_{50} \sim 1.8\,B \sim 1.75\,T_{50}, W_r \sim 70\%$ of the write width (W_w) and $W_w \sim 70\%$ of the track pitch (W_p). We first apply this scaling to both media and then, following the discussion at the end of Section V, track edge effects are included by either reducing the density by 20% at a fixed SNR or decreasing the SNR by 1 dB at a fixed density.

Fig. 9 plots SNR versus density for both tilted and conventional perpendicular recording, each for two bit-aspect ratios, $\beta = W_p/B = 4$ and 8. For tilted perpendicular recording, we assume an optimum case with transition parameter $a/\bar{D} = 1/3$ and crosstrack correlation width $s_c = \bar{D}$. For conventional perpendicular recording, we assume two cases: CP1) an optimal case with transition parameter $a/\bar{D} = 1/3$ and crosstrack correlation width $s_c = \bar{D}$; CP2) a realistic case utilizing the micromagnetic simulation result in Section IV, with transition parameter $a/\bar{D} = 0.46$ and crosstrack correlation width $s_c = \bar{D}$. $\bar{D}$ is the average grain size from (9) for tilted perpendicular media and (11) for conventional perpendicular media.

The results show that for same recording medium thickness and bit-aspect ratio ($t = 20$ nm, $\beta = 4$ or 8), there is a 9.6-dB gain in SNR in tilted perpendicular recording as compared to optimal conventional perpendicular recording (CP1). For more realistic conventional perpendicular recording (CP2), a gain of 12.6 dB occurs at all densities. For example, for a medium thickness of $t = 20$ nm, with a 15-dB SNR tolerance, Fig. 9 shows that for $\beta = 4, 8$, for tilted perpendicular recording, the limited recording densities are 1.7 and 1.4 Tb/in^2, respectively. In conventional perpendicular recording (CP2), the limits will be 200 and 160 Gb/in^2, respectively. Note that from the track edge discussion at the end of Section V, these limits for conventional perpendicular recording are reduced by 20% in addition to the estimate from (16).

Table II shows SNR estimates, utilizing (9), (11), and (16), for different medium thicknesses, at two different densities: 200 and 1000 Gb/in^2. In this table, the bit-aspect ratio is $\beta = 4$ and the temperature is $T = 360$ K. As seen in Fig. 9, there is a additional 1.5-dB SNR decrease for $\beta = 8$ as compared to $\beta = 4$ for both

TABLE II
SNR FOR TILTED PERPENDICULAR (TP) AND CONVENTIONAL PERPENDICULAR RECORDING (CP1 AND CP2)

$SNR_{(dB)}$	$200_{Gbit/in^2}$			$1000_{Gbit/in^2}$		
$t_{(nm)}$	TP	CP1	CP2	TP	CP1	CP2
25	30.6	21.0	18.0	20.1	10.5	7.5
20	29.1	19.5	16.5	18.6	9.0	6.0
15	27.2	17.6	14.6	16.7	7.2	4.2
12	25.8	16.2	13.2	15.3	5.7	2.7

tilted perpendicular and conventional perpendicular recording. Note that for a system operating at 200 Gb/in^2, the transition noise limited SNR in tilted perpendicular recording is about 29 dB and only 16.5 dB for realistic conventional perpendicular recording (CP2).

We note that for an SNR gain of 12.6 dB in tilted perpendicular recording as compared to realistic conventional perpendicular recording, about 8–9 dB is from the larger H_k and M_s values. A smaller transition parameter in tilted perpendicular recording yields another 2–3 dB and 1 dB is from the track edge effect.

VIII. DISCUSSION

In this paper, our goal has been to present the concept of tilted perpendicular recording in a reasonably complete manner. We have shown by considering major system aspects that this new format yields a significant increase in SNR and data rate compared to conventional perpendicular recording. A variety of issues need yet to be explored and that will be the focus of subsequent papers; for example, the effect of orientation distributions, including dc noise, details of the effect of intergranular exchange on thermal stability, and the effect of geometry scaling on maximum anisotropy. However, here we wish to present an overview of these additional issues that are only briefly touched upon in this paper. A critical issue is the manufacturability of this media and that question is not addressed here.

A primary issue is the nature of the “tilting” and the associated distributions. For simplicity, the analysis here focuses on a tilted perpendicular medium design, where only the grain anisotropy axes are angled at about 45° in the crosstrack direction. A large variety of orientation variations are possible. The angular deviation from the perpendicular direction could conceivably be in any azimuthal direction in the film plane. It is also possible to consider the grain anisotropy axes at a fixed angle from the perpendicular, but with azimuthal anisotropy direction varying randomly from grain to grain (as might occur for various epitaxial growth mechanisms). Here, the case of solely crosstrack orientation was examined, simply because the pulse shape would not vary between the TP and CP media. Random orientation would give rise to considerable dc or uniform magnetization noise. Track signal uniformity would require tilting in either the cross or downtrack directions. In both cases, a distribution of orientations about a design angle would also yield dc noise, which might be more severe for downtrack orientation. DC noise was neglected in this first work and must be considered to include orientation distributions in a cone about the average orientation. Initial micromagnetic simulations indicate that crosstrack anisotropy axis tilting is an optimal configuration.

For a given tilt direction, it is possible to consider a tilting of the grain shape as well. Magnetostatic effects will be increased, but these might be small if a small value of M_s/H_k is maintained as in this paper (~ 0.02). However, similar to tilted tape media (MET) where the grains are deposited at an angle to the film plane, additional problems such as surface roughness as well as the increased effective diameter in the medium plane could be a factor.

In the analytic analysis of thermal stability, the role of exchange on the energy barriers was considered only approximately. For a given grain, the neighboring grain exchange fields should be included (e.g., [9], [38]). Inclusion of exchange affects stability away from the transition center in the saturated regions, but not, to first order, at the transition center, where the average magnetization vanishes. Because the (ferromagnetic) exchange field opposes the demagnetization field in the saturated (low-density) regions, the energy barriers of (8) and (10) are, in fact, larger. Including exchange yields the transition center as the most thermally vulnerable region and, as will be discussed in [39], the net effect does allow for reduced grain sizes and increased density limits.

Density limit scaling in this paper was done by scaling the head-medium dimensions, but with a fixed value of anisotropy, determined by the 200 Gb/in^2 geometry. Reducing head dimensions but maintaining the medium thickness for thermal stability reduces the maximum field somewhat.

Finally, it must be noted that the density limits shown here are very simplified: a large variety of material and geometric optimizations must be done including the issues raised above as well as examining distributions of anisotropy magnitude. The primary goal of this paper is not to determine ultimate density limits of tilted and conventional perpendicular recording, but to show the major differences between these two recording configurations. The major conclusion is that, given reasonably tight material distributions, tilted perpendicular recording will achieve about a 10–12 dB gain in SNR compared to conventional perpendicular recording.

IX. CONCLUSION

A new magnetic recording method called tilted perpendicular recording was introduced. The central design includes a medium anisotropy direction that is tilted at a certain angle optimally about 45° with respect to the perpendicular direction. The main effect is that a medium with much higher anisotropy can be utilized as compared to conventional perpendicular recording. For a given thermal stability criterion, this increase in anisotropy allows for a much smaller medium grain diameter. Using both analytical and numerical analyses, it is shown that at a fixed density, there is approximately a 12.6-dB gain in SNR for tilted perpendicular media versus realistic conventional perpendicular media. The maximum anisotropy field is about 28 000 Oe, when a tapered single-pole head with a very small throat height is utilized (with head saturation $B_s = 2.4$ T). Tilted perpendicular magnetic recording allows for a higher data rate than in conventional perpendicular recording, due to enhanced reversal torque. Tilted perpendicular recording also provides a narrower erase band and, therefore, a larger track density due to increased grain energy stability at the track edges.

As an example, for a medium transition noise SNR of 17 dB and bit-aspect ratio $\beta = 4$, tilted perpendicular recording yields a density limit of about 1.3 Tb/in^2 with a data rate of about 1.5 Gb/s (0.1-ns head field rise time). In comparison, for the same SNR, the limit in conventional perpendicular recording is predicted to be about 160 Gb/in^2 with a data rate about 700 Mb/s.

ACKNOWLEDGMENT

The write field simulation utilized the IBM Blue Horizon at San Diego Supercomputer Center. The authors wish to thank X. Wang for helpful discussion on thermal stability, and Dr. H. Zhou, Z. Jin, and B. Valcu for helpful discussions.

REFERENCES

[1] H. Takano, Y. Nishida, A. Kuroda, H. Sawaguchi, T. Kawabe, and A. Ishikawa, “A practical approach for realizing high-recording-density hard disk drives,” in *8th Joint Intermag-MMM Conf.*, San Antonio, TX, 2001, Abstract CA-01.

[2] M. Yamagishi, “Over 100 Gbit/in^2 longitudinal magnetic recording,” in *Intermag 2002*, Amsterdam, The Netherlands, Paper BA-02.

[3] Z. Zhang, Y. C. Feng, T. Clinton, G. Badran, N-H. Yeh, G. Tarnopolsky, E. Girt, M. Munteanu, S. Harkness, H. Richter, T. Nolan, R. Ranjan, S. Hwang, G. Rauch, M. Ghaly, D. Larson, E. Singleton, V. Vas’ko, J. Ho, F. Stageberg, V. Kong, K. Duxstad, and S. Slade, “Magnetic recording demonstration over 100 Gbit/in^2,” *IEEE Trans. Magn.*, vol. 38, pp. 1861–1866, Sept. 2002.

[4] K. Stoev, F. Liu, Y. Chen, X. Dang, J. Wang, H. Jiang, Y. Liu, P. Luo, L.-C. Wang, R. Esch, J. Chen, S. F. Gu, C. Liu, K. T. Kung, M. Lederman, and M. Re, “High linear density study of advanced single-pole head,” *IEEE Trans. Magn.*, vol. 38, pp. 2243–2248, Sept. 2002.

[5] H. N. Bertram and M. Williams, “SNR and density limit estimates: A comparison of longitudinal and perpendicular recording,” *IEEE. Trans. Magn.*, vol. 36, pp. 4–9, Jan. 2000.

[6] K. Gao and H. N. Bertram, “Write field analysis for perpendicular recording using 3D micromagnetic simulation,” *J. Appl. Phys.*, vol. 91, pp. 8369–8371, June 2002.

[7] H. Zhou and H. N. Bertram, “Micromagnetic analysis of the effect of intergranular exchange on thermal stability in magnetic recording. I. Two-dimensional isotropic longitudinal media,” *IEEE Trans. Magn.*, vol. 38, pp. 1405–1416, Mar. 2002.

[8] ——, “Micromagnetic analysis of the effect of intergranular exchange on thermal stability in magnetic recording. II. Slight oriented longitudinal media,” *IEEE Trans. Magn.*, vol. 38, pp. 1417–1421, Mar. 2002.

[9] H. Zhou, H. N. Bertram, and M. E. Schabes, “Micromagnetic analyses of the effect of intergranular exchange on thermal stability in magnetic recording. III. Perpendicular media,” *IEEE Trans. Magn.*, vol. 38, pp. 1422–1428, Mar. 2002.

[10] M. Mallary, A. Torabi, and M. Benakli, “One terabit per square inch perpendicular recording conceptual design,” *IEEE. Trans. Magn.*, vol. 38, pp. 1719–1724, July 2002.

[11] N.-Y. Park *et al.*, “High density perpendicular magnetic recording with ring head,” *IEEE. Trans. Magn.*, to be published.

[12] R. Wood, “The feasibility of magnetic recording at 1 terabit per square inch,” *IEEE. Trans. Magn.*, vol. 36, pp. 36–42, Jan. 2000.

[13] D. A. Thompson, “The role of perpendicular recording in the future of hard disk storage,” *J. Magn. Soc. Jpn.*, vol. 21, pp. 9–15, 1997. Supplement S2.

[14] T. Ishida *et al.*, “More than 1 Gb/in^2 recording on obliquely oriented thin film tape,” *IEEE. Trans. Magn.*, vol. 36, pp. 183–188, Jan. 2000.

[15] H. J. Richter, “An approach to recording on tilted media,” *IEEE. Trans. Magn.*, vol. 29, pp. 2258–2265, Sept. 1993.

[16] C. H. Hee, Y. Y. Zou, and J. P. Wang, “Tilted media by micromagnetic simulation: A possibility for the extension of longitudinal magnetic recording?,” *J. Appl. Phys.*, vol. 91, pp. 8004–8006, June 2002.

[17] Y. F. Zheng, J. P. Wang, and V. Ng, “Control of the tilted orientation of CoCrPt/Ti thin film media by collimated sputtering,” *J. Appl. Phys.*, vol. 91, pp. 8007–8009, June 2002.

[18] K. Z. Gao and H. N. Bertram, “Write field analysis and write pole design in perpendicular recording,” *IEEE. Trans. Magn.*, vol. 38, pp. 3521–3527, Sept. 2002.

[19] Z. Jin, M. Doerner, and N. Bertram, “A growth model for polycrystalline thin film media: Comparison of bicrystal and unicrystal grain structures,” *IEEE. Trans. Magn.*, vol. 36, pp. 2294–2296, Sept. 2000.

[20] B. Valcu, Y. Takahashi, and H. N. Bertram, “Effect of crystallographic orientation on grain size distribution,” *J. App. Phys.*, to be published.

[21] J. G. Zhu and H. N. Bertram, “Micromagnetic studies of thin metallic films,” *J. Appl. Phys.*, vol. 63, p. 3248, 1988.

[22] E. C. Stoner and E. P. Wohlfarth, *Philos. Trans. R. Soc.*, vol. 1-240, p. 74, 1948.

[23] K. Z. Gao and H. N. Bertram, “3-D micromagnetic simulation of write field rise time in perpendicular recording,” *IEEE. Trans. Magn.*, vol. 38, pp. 2063–2065, Sept. 2002.

[24] L. Néel, “Experimental remarks on ferromagnetism at low temperatures,” *Progr. Low Temperature Phys.*, vol. 1, pp. 337–343, 1955.

[25] X. Wang, H. N. Bertram, and V. Safanov, “Thermal dynamic reversal of fine magnetic grains with arbitrary anisotropy axes orientation,” *J. Appl. Phys.*, vol. 92, pp. 2064–2072, Aug. 2002.

[26] H. N. Bertram, X. Wang, and V. L. Safanov, “Dynamic-thermal effects in thin film media,” *IEEE. Trans. Magn.*, vol. 37, pp. 1521–1527, July 2001.

[27] N. Inaba, Y. Uesaka, and M. Futamoto, “Compositional and temperature dependence of basic magnetic properties of CoCr-alloy thin films,” *IEEE. Trans. Magn.*, vol. 36, pp. 54–60, Jan. 2000.

[28] M. F. Doerner, private communication.

[29] M. L. Williams and R. L. Comstock, “An analytical model of the write process in digital magnetic recording,” in *AIP Conf. Proc.*, vol. 5, 1971, pp. 738–742.

[30] H. N. Bertram, *Theory of Magnetic Recording*. Cambridge, U.K.: Cambridge Univ. Press, 1994.

[31] Y. Zhang and H. N. Bertram, “Thermal decay of signal and noise in high density thin film media,” *IEEE. Trans. Magn.*, vol. 35, pp. 4326–4338, Sept. 1999.

[32] H. N. Bertram and H. J. Richter, “Arrhenius-Nèel thermal decay in polycrystalline thin film media,” *J. Appl. Phys.*, vol. 85, no. 8, pp. 4991–4993, 1999.

[33] M. Benakli, A. F. Torabi, M. L. Mallary, H. Zhou, and H. N. Bertram, “Micromagnetic study of switching speed in perpendicular recording media,” *IEEE Trans. Magn.*, vol. 37, pp. 1564–1566, July 2001.

[34] Q. Peng and H. N. Bertram, “Micromagnetic studies of switching speed in longitudinal and perpendicular polycrystalline thin film recording media,” *J. Appl. Phys.*, vol. 81, pp. 4384–4386, 1997.

[35] K. Z. Gao and H. N. Bertram, “Media switching speed in tilted and conventional perpendicular recording,” *IEEE Trans. Magn.*, to be published.

[36] V. L. Safonov and H. N. Bertram, “Dynamic-thermal reversal in a fine micromagnetic grain: Time dependence of coercivity,” *J. Appl. Phys.*, vol. 87, p. 5681, 2000.

[37] B. Valcu, T. Roscamp, and H. N. Bertram, “Pulse shape, resolution and signal-to-noise ratio in perpendicular recording,” *IEEE. Trans. Magn.*, vol. 38, pp. 288–294, Jan. 2002.

[38] R. H. Victora, K. Senanan, and J. Xue, “Areal density limits for perpendicular magnetic recording,” *IEEE. Trans. Magn.*, vol. 38, pp. 1886–1891, Sept. 2002.

[39] K. Z. Gao and H. N. Bertram, “Transition jitter estimates in tilted and conventional perpendicular recording media at 1 Tb/in^2,” *IEEE. Trans. Magn.*, to be published.